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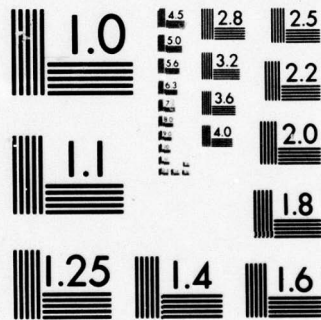
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Stimulation of Pc 1 Micropulsations by Controlled VLF Transmissions

Space Sciences Laboratory
The Ivan A. Getting Laboratories
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El Segundo, Calif. 90245

7 April 1977

Interim Report

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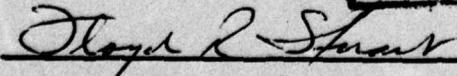
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repetitive program the pulsations recurred every 90 sec. The micropulsations onset 15 minutes after satellite 1972-76B, at low altitude in the conjugate region of the transmitter, observed proton fluxes which could be identified on a one-for-one basis with irregularly-spaced pulses from the transmitter. Calculations suggest that the 6.6 kHz whistler-mode wave and a 1 Hz hydromagnetic wave resonate with protons of the same parallel velocity near $L = 4.0$. The observations suggest that the micropulsations were stimulated by the VLF transmissions with the protons playing a role in the interaction.

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PREFACE

The author is indebted to the Commander, U.S. Army, Alaska for the use of the restricted air space at Fort Richardson, Alaska; and to W. H. Campbell, R. L. Dowden, and R. R. Heacock for the micropulsation data. It is a pleasure to acknowledge productive discussions with M. Schulz. I am grateful to Lynn Friesen for the computer calculations.

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INTRODUCTION

Experiments designed to artificially generate ultra-low-frequency (ULF) waves were undertaken in conjunction with controlled very-low-frequency (VLF), wave transmissions conducted at Fort Richardson, Alaska (L4). approximately

Pc 1 micropulsations are believed to be produced by a Doppler-shifted, resonant interaction between Alfvén waves and moderately-energetic, ring-current protons [Jacobs, 1970]. This interaction is analogous to the interaction between VLF whistler-mode waves and energetic electrons. The interaction occurs between waves and particles traveling in "opposite" directions along a magnetic field line. An anomalous interaction can also occur between VLF whistler-mode waves overtaking protons traveling in the same direction along the magnetic field line.

Recent evidence statistically associates Pc 1 micropulsation onsets with controlled VLF transmissions [Fraser-Smith and Cole, 1975] and suggests that the preferred ULF frequency is a harmonic of the modulation frequency of the VLF transmitter [Willis and Davis, 1976].

Dynamic spectra of micropulsation data taken at College, Alaska during the time period of the VLF transmission experiments performed at Fort Richardson, Alaska have been analyzed for evidence of Pc 1 micropulsation events which correlate with the VLF transmissions.

One Pc 1 micropulsation event containing strong periodicities that correlate with the transmitter modulation frequency will be described here. It is noteworthy that this event occurred only 15 minutes after the data acquisition by satellite 1972-76B over New Zealand during which

precipitated protons were observed which could be correlated on a pulse-by-pulse basis with the VLF transmission program [Koons, 1975].

The transportable, very-low-frequency (TVLF) transmitter facility described by Koons and Dazey [1974] was used for these experiments. The transmissions took place at Fort Richardson, Alaska, 61.4°N , 210.4°E , between 1 August and 14 September 1973. The site is located on an L-shell of 4.1.

The transmitter consists of a 150-kW power amplifier. The antenna is a nearly vertical conducting cable supported by a helium balloon. The antenna also serves as the balloon tether and is deployed and retrieved by a winch. The operating height of the present system is limited to 1200 m by the lift of the 1000 m^3 balloon.

Transmissions were conducted at 6.6, 7.4, 7.8, 8.0, 13.275, and 21.0 kHz. Under normal operating conditions, the system radiated 100W at 6.6 kHz and 1400W at 13.3 kHz.

The data analyzed in this study were obtained by six electromagnetic pulsation detection systems. The types and locations of the detectors are listed in Table 1.

Table 1. Sources of magnetometer data analyzed in this study.

<u>Instrument</u>	<u>Location</u>	<u>Components Measured</u>	<u>Organization</u>
Induction Loop (air core)	College, Alaska	H, D	U.S. Geological Survey
Induction Loop (air core)	Boulder, Colorado	H, D	U.S. Geological Survey
Induction Loop (air core)	Soldynka, Finland	H, D	U.S. Geological Survey
Induction Loop (large-area ground plane)	Dunedin, New Zealand	Z	Dept. of Physics, University of Otago
Induction Loop	College, Alaska	H	Geophysical Institute, University of Alaska
Induction Loop	Macquarie Island	H, D	Geophysical Institute, University of Alaska

MAGNETOMETER DATA

Between August 1st and September 14th, 34 Pc 1 micropulsation events were detected by the induction-loop antenna (H component) operated by the U. S. Geological Survey at College, Alaska. The induction magnetometers were "style 5" antenna systems described by W.H. Campbell [1969]. Only one of these events occurred while the TVLF transmitter was in operation. This unusually low overlap can be accounted for by comparing the local time of occurrence of Pc 1's with the normal transmitting schedule of the VLF transmitter. The number of one-hour intervals with Pc 1 activity is shown in Fig. 1 as a function of Universal Time (UT). The activity is strongly peaked at 00 hr UT (local geomagnetic noon is 23:38 UT). However, the transmitter was normally operated from 09:30 to 15:30 UT (local nighttime), with infrequent operations from 06:30 to 09:30 and 15:30 to 20:00. These hours of operation were dictated by the requirements of the other users of the restricted air space at Fort Richardson. The Pc 1 micropulsations which occurred during the VLF transmissions onset at 11:53 and terminated at 12:21 UT on 11 September. A spectrogram of that event is shown in Fig. 2. In Fig. 2, the strong horizontal line at 1.5 Hz and the weaker horizontal lines at approximately 0.1, 0.6, 0.9, and 1.2 Hz are interference lines. Although the origin of these interference lines is not known, they are not related to the operation of the TVLF transmitter. On September 11, 1973, they occurred in the micropulsation data continuously throughout the day appearing unchanged before, during and after the scheduled interval of VLF transmissions on that day.

Between 11:30 and 11:50 UT, the transmitted programs consisted of pulse sequences with irregular pulse durations and spacings. A new program was initiated every five minutes and the pulse sequence within a program repeated at 30-sec intervals for the program between 11:35 and

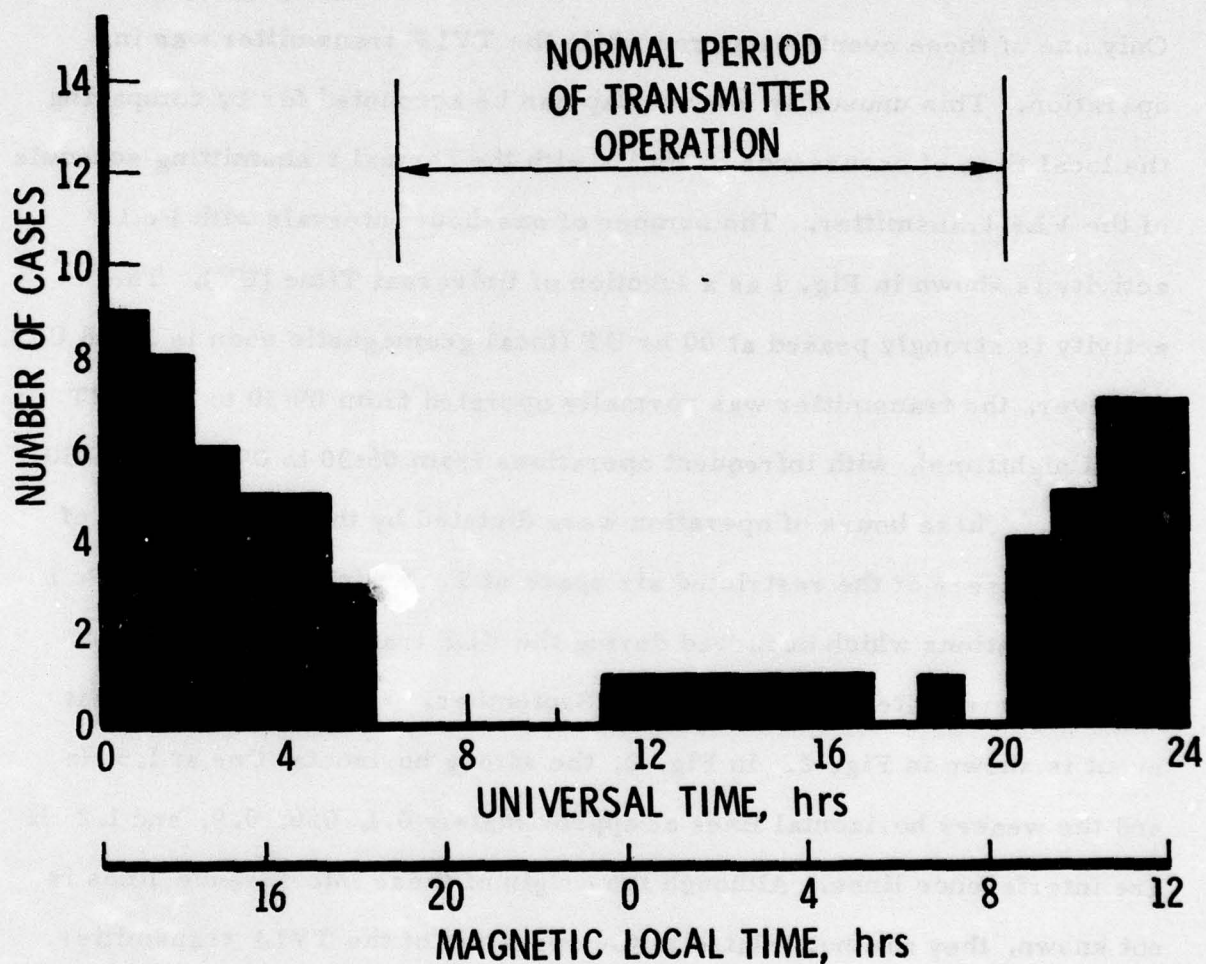


Figure 1. Histogram of the occurrence of Pc 1 micropulsations as a function of time between 1 August and 14 September 1973.

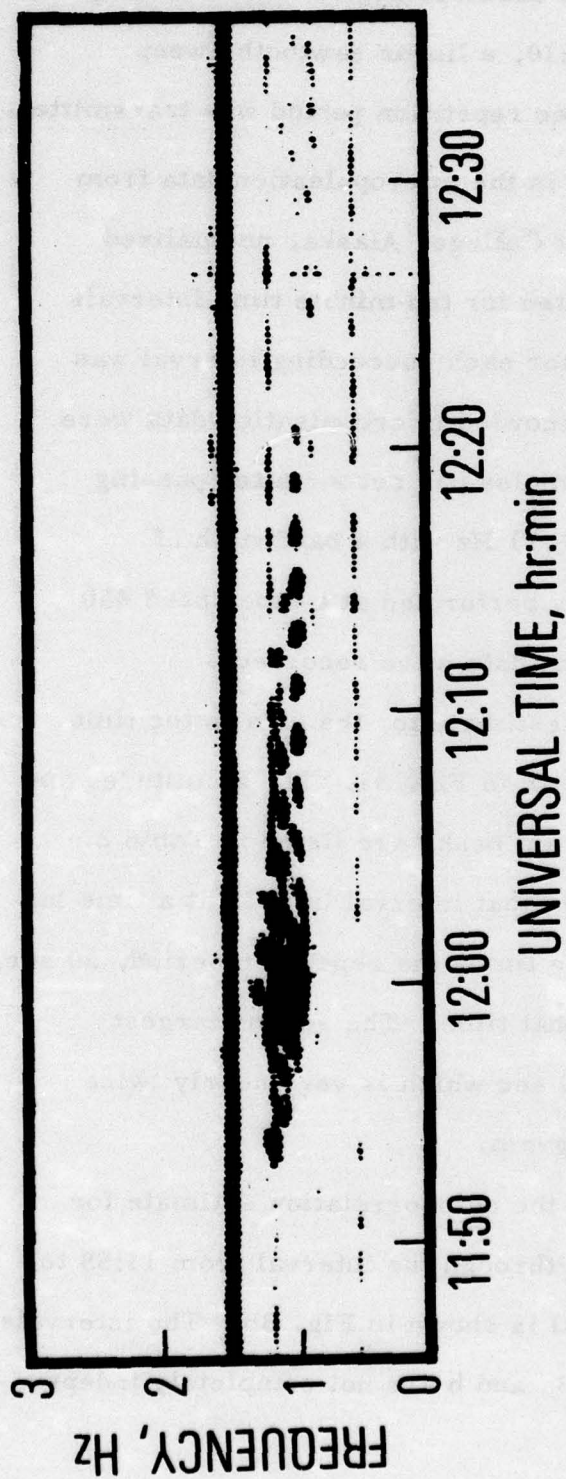


Figure 2. Spectrogram of micropulsation event on 11 September 1973 plotted as a function of Universal Time. The strong horizontal line at 1.5 Hz and the weaker horizontal lines at approximately 0.6, 0.6, and 1.2 Hz are interference lines.

11:40 and at 60-sec intervals for the others. Between 11:50 and 12:00, a simple pulse program was transmitted. It consisted of a 5-sec long pulse every 30 sec. The micropulsation event shown in Fig. 2 started during this time period. Between 12:00 and 12:10, a linear sawtooth sweep between 6553 Hz and 6647 Hz with a 5-sec repetition period was transmitted.

In order to identify periodicities in the micropulsation data from the U.S. Geological Survey detector at College, Alaska, normalized autocorrelation estimates were computed for ten-minute time intervals starting at 11:52 UT. The start time for each succeeding interval was advanced by two minutes. The tape recorded micropulsation data were digitized at an effective rate of 0.1 samples per second after passing through a bandpass filter centered at 1.11 Hz with a bandwidth of ± 0.167 Hz (the processing was actually performed at a tape speed 450 times faster than the speed at which the data were recorded).

The normalized autocorrelation estimate for the data in the time interval from 11:52 to 12:02 UT is shown in Fig. 3a. The amplitudes and corresponding time lags for the dominant peaks are listed in Table 2. The largest autocorrelation estimate in that interval is 0.38 at a time lag of 90.4 sec. This is very nearly three times the repetition period, 30 sec, of the TVLF program in progress at that time. The second largest amplitude occurs at a time lag of 59.9 sec which is very nearly twice the repetition period of the TVLF program.

The general features present in the autocorrelation estimate for the 11:52 to 12:02 UT interval persist through the interval from 11:58 to 12:08 UT. The data from that interval is shown in Fig. 3b. The intervals used for the analysis shown in Figs. 3a and b are not completely independ-

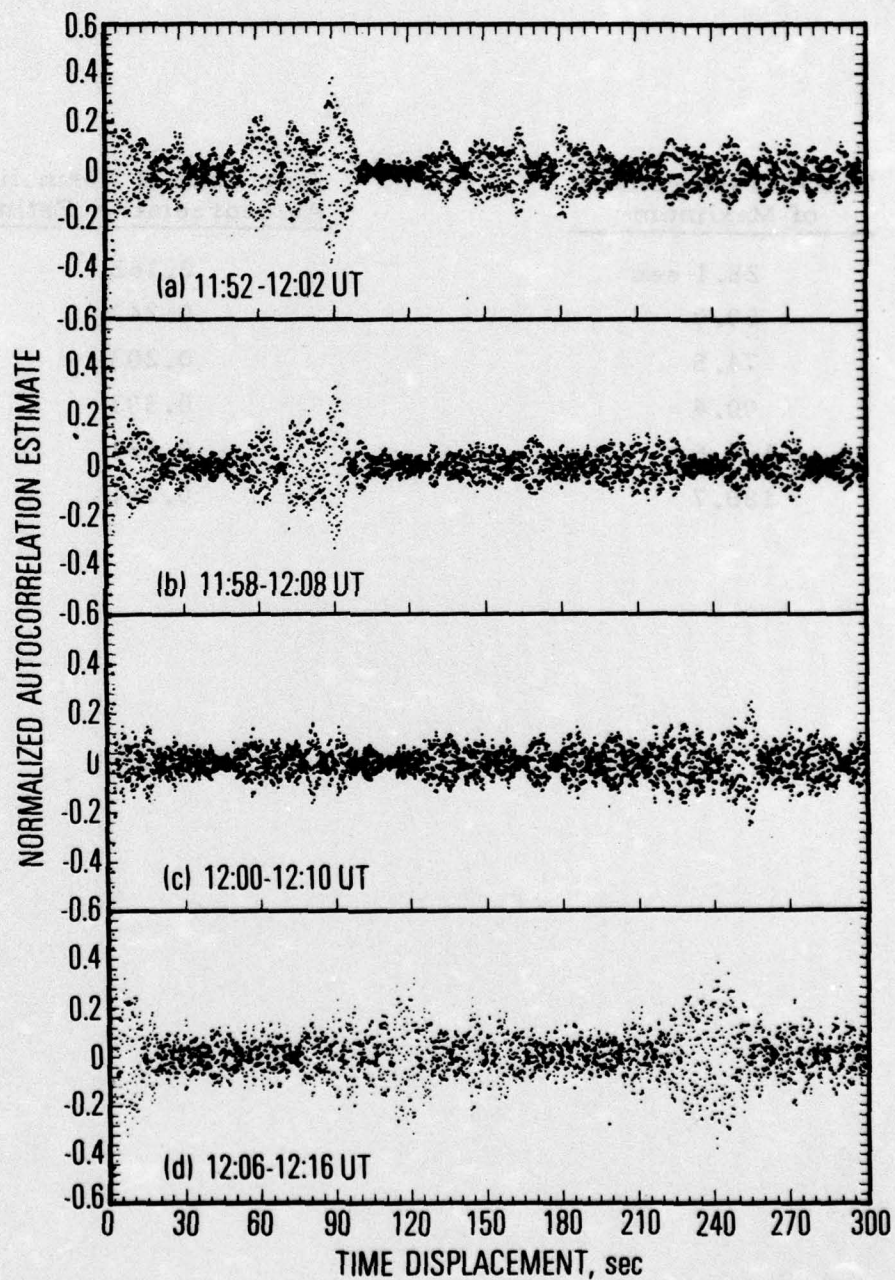


Figure 3. Autocorrelograms of the micropulsation data in the band 1.11 ± 0.167 Hz in four ten-minute time intervals.

Table 2. Maxima in the normalized autocorrelation estimate with amplitudes greater than 0.15 for the Pc 1 micropulsation data for the time interval from 11:52 to 12:02 UT.

<u>Time-Displacement of Maximum</u>	<u>Amplitude of Normalized Autocorrelation Estimate</u>
28.1 sec	0.162
59.9	0.242
74.5	0.203
90.4	0.382
164.5	0.181
180.7	0.191

ent since there is a four-minute overlap.

A significant change occurs in the autocorrelation estimate at 12:00 UT. The autocorrelation estimates computed for intervals after 12:00 UT have dominant maxima at 240 sec and 120 sec. The autocorrelation estimate for the interval from 12:00 to 12:10 UT is shown in Fig. 3c. The autocorrelation estimate for the period from 12:06 to 12:16 UT is shown in Fig. 3d.

The 120-sec period in the interval from 12:06 to 12:16 UT is the repetition period of the monochromatic wave at 1 Hz which is evident in the dynamic spectra in Fig. 2.

Autocorrelation estimates for time intervals prior to the onset of the Pc 1 event show no evidence of periodicities at simple multiples of 30 sec.

This micropulsation event is also present on a sonagram from a detector on Macquarie Island ($L = 5.2$). At Macquarie, the signal appears to be stronger in H than in D. R.R. Heacock (private communication, 1975) notes that this is consistent with propagation of the signal via the F-layer duct from a source line inwards from Macquarie. The Pc 1 event appears to be more intense at College than at Macquarie.

These observations were made during the recovery stage of a moderate magnetic storm which injected ring current protons into the inner magnetosphere. The hourly equatorial Dst values reached a minimum of -73γ at 22 hr UT on September 9. By 12 hr UT on September 11, Dst had recovered to -10γ .

INTERPRETATION

Simultaneous Resonance. Since the Pc 1 micropulsations and the precipitating protons [Keons, 1975] exhibit temporal structures that correlate with the pulsed modulation of the TVLF transmitter and, since the events were observed within a short span of time, a complex interaction involving whistler-mode waves, protons, and Alfvén waves may be involved in the separate observations.

It is possible for the same protons to be in resonance with a non-ducted, whistler-mode wave and an Alfvén wave propagating parallel to the geomagnetic field direction.

The component of velocity parallel to the magnetic field of a proton that resonates with a non-ducted, whistler-mode wave of frequency $\omega/2\pi$ is given by:

$$v_{\parallel}^2 = \frac{\omega c^2 (\omega_{be} \cos \theta - \omega)}{\cos^2 \theta \omega_p^2} \quad (1)$$

That which resonates with a parallel propagating Alfvén wave of frequency $\Omega/2\pi$ is given by [Obayashi, 1965]:

$$v_{\parallel}^2 = (1 - \Omega/\omega_{bi})^3 v_A^2 / (\Omega/\omega_{bi})^2 \quad (2)$$

In (1) and (2), ω_{be} and ω_{bi} are the electron and ion gyro frequencies respectively, c is the speed of light, θ is the wave-normal angle, ω_p is the plasma frequency, and v_A is the Alfvén velocity.

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The conditions for simultaneous resonance are obtained by equating the right hand sides of (1) and (2). This yields a relationship between θ , ω_{bi} , ω_{be} , ω , and Ω . It is interesting to note that since the plasma density enters through ω_p^2 in the same way in the denominators of both (1) and (2), the simultaneous resonance is independent of electron density. The parameters for simultaneous resonance for $\omega/2\pi = 6.6$ kHz and $\Omega/2\pi = 1$ Hz are given in Table 3. On L shells between $L = 3.8$ and $L = 4.2$, the wave-normal angle of the whistler-mode wave must lie between 55° and 65° . As noted by Koons [1975] the wave-normal angle at the equator, obtained by a whistler-mode ray-tracing program for the diffusive-equilibrium density distribution used to model the proton precipitation event, was always found to be quite close to 60° .

Micropulsation Bounce Period. From 12:06 to 12:16 UT there is a definite 120 sec recurrence period in the micropulsations at 1 Hz. The autocorrelation estimates computed for intervals after 12:00 UT have dominant maxima at 240 sec and 120 sec. This suggests that either 120 sec or 240 sec is the micropulsation bounce period.

Campbell [1967] shows a scatter plot of the relationship of recurrence periods and mid-periods for 145 Pc 1 events at College, Alaska from August 1963 to February 1964. At 1 Hz the recurrence period varies from 90 sec to 150 sec. As the frequency of the Pc 1 decreases, the recurrence period increases. For a recurrence period of 240 sec, the frequency range is approximately 0.3 to 0.5 Hz. If we identify the recurrence period with the micropulsation bounce period, then these data strongly suggest that the bounce period for the September 11 event was 120 sec.

Table 3. Wave-normal angle required for a 6.6 kHz whistler-mode wave and a parallel propagating 1 Hz Alfvén wave to resonate with the same proton population.

<u>L Shell</u>	<u>Wave-Normal Angle</u>
3.8 R_e	64.5 deg
4.0	60.1
4.2	54.9

Using the method developed by Watanabe [1965], the group bounce period for 1 Hz Alfvén waves has been calculated as a function of equatorial electron density for a field line at $L = 4$. The group bounce period for two magnetospheric plasma density distributions is plotted in Fig. 4. The number density of the electrons is assumed to be proportional to B^n , where B is the local magnetic field and n is a power index. Watanabe [1965] tabulates the required integral for $n = 0, 1$, and 2 . A diffusive equilibrium model lies between $n = 0$ and $n = 1$. For a group bounce period of 120 sec the equatorial electron density at $L = 4$ for the model with $n = 1$ is 380 cm^{-3} and for $n = 0$, 700 cm^{-3} .

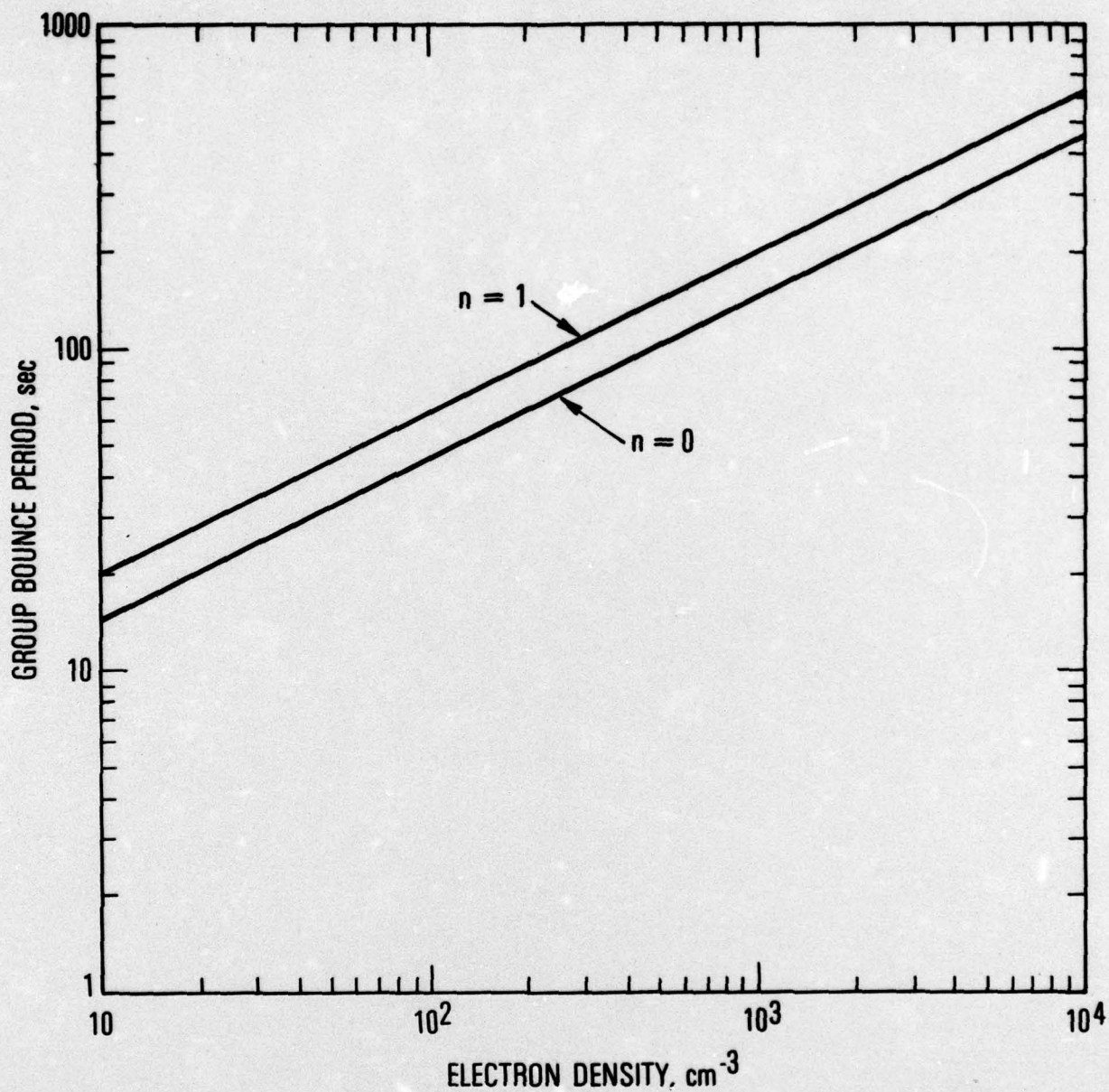


Figure 4. Group bounce period for a 1 Hz Alfvén wave on a field line at $L = 4$ as a function of the equatorial electron density. $n = 1$ corresponds with a distribution in which the electron density is proportional to the local magnetic field. $n = 0$ corresponds to a uniform density along the field line.

DISCUSSION

The micropulsation and proton observations on September 11, 1973 suggest that a complex interaction occurred between VLF whistler-mode waves, ULF Alfvén waves and energetic protons on a field line near $L=4$. The parameters are such that $\omega_{be} \cos \theta$ is rapidly approaching ω in (1) as L increases. This means that the $v_{||}^2$ is rapidly decreasing and, as a consequence, that the proton bounce period is increasing. At $L \approx 4.05$, $v_{||} = 0$. Between $L = 3.9$ and $L = 4.05$, the non-ducted whistler-mode wave will resonate with protons having bounce periods of both 60 sec and 90 sec. The proton bounce period is consistent with an anomalous doppler-shifted resonance interaction between the protons and a non-ducted whistler-mode wave from the TVLF transmitter. Protons of the same energy also resonate with 1 Hz Alfvén waves near $L=4$. The observed Alfvén wave bounce period, 120 sec, after 12:00 UT is consistent with an echoing wave along an $L=4$ field line.

The autocorrelation estimate contains maxima at simple multiples of the repetition period of the TVLF program between 11:52 and 12:02 UT. During this time period, the dynamic spectra shows a complex frequency structure suggesting that side-band formation, as described by Roux et al. [1973], is taking place. The correlation with the TVLF program suggests that the Alfvén wave generation is being driven by the 6.6 kHz whistler-mode waves from the VLF transmitter. The 90-sec period, which is dominant in the autocorrelation estimate, may be the bounce period of the resonant protons.

The micropulsation event discussed here is similar to the periodically structured Pc 1 micropulsations described by Heacock and Akasofu [1973] and Mullen and Heacock [1972]. Those authors show that structured Pc 1 micropulsations occur during the late recovery phase of geomagnetic storms when the plasmasphere has filled sufficiently from the ionosphere. Their data demonstrate that Pc 1 field lines are within the plasmasphere, i. e. on field lines with plasma densities between 20 and 350 cm^{-3} . This is somewhat lower than the range of densities, 380 to 700 cm^{-3} that we have calculated from the bounce period for the September 11 event.

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